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A random walk in radiation physics

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Abstract . There are several areas in radiation physics which are yet to be properly explored Some of these unsolved problems in the field of radiation physics of gamma ray photons are discussed in the paper

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1. Introduction

When a field of crops has been harvested, harvesters are often followed by gleaners, persons who collect the residuals of overlooked or neglected crops. The present paper is an attempt by a gleaner in the field of radiation physics to draw the attention of other gleaners, especially the younger ones, to some as yet unsolved problems in the field of gamma ray radiation physics. The investigations proposed below have been rather randomly chosen apart from the fact that they have the unifying common feature of, directly or indirectly exploiting simple geometrical symmetries in their experimental set up. More specifically we shall be concerned with :

(a) investigations on the coherent scattering of gamma rays by atoms in the energy band in which Rayleigh scattering is the dominant component of coherent scattering,

(b) the design considerations of an experimental arrangement for the measurement of total cross section of samples available in the gaseous form,

(c) investigate the conditions under which a modified cylindrical transmission is exactly equivalent, in the limit, to sphere transmission. Measurement of energy absorption and photoelectric cross sections and

(d) explore the feasibility of developing an intense source of gamma rays of smoothly variable energy for studying nuclear resonance scattering.

2. Investigations on Rayleigh scattering

(i) It is well-known that the coherent scattering of gamma rays can take place through a number of processes like nuclear Thompson scattering, Rayleigh scattering, Delbruck scattering *etc.* We shall focus our attention to the energy range of photons where Rayleigh scattering is the dominant coherent process such that the coherent scattering cross section is essentially given by the Rayleigh scattering cross section.

Comparison of experimental and theoretical values of differential coherent scattering cross sections is an important exercise in the energy range under consideration. While making this comparison, possible errors in the quoted values of the cross sections must be included, so that one can assign error limits to the ratios of experimental and the corresponding theoretical cross sections.

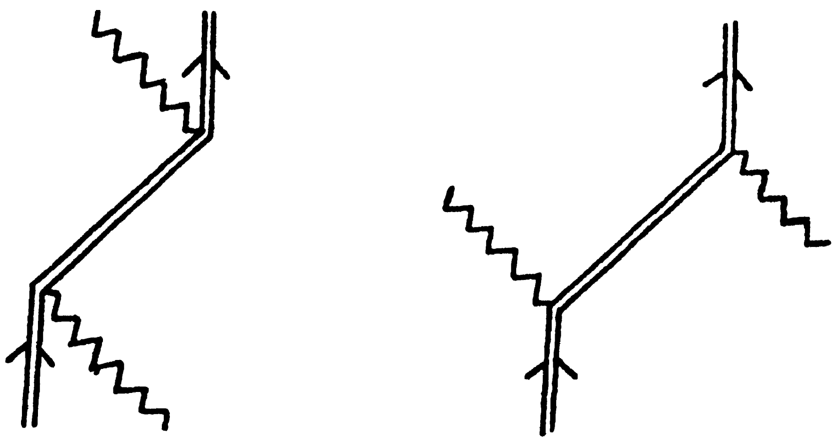
(ii) *Rayleigh scattering : theory*

According to the lowest nonvanishing order of perturbation theory, Rayleigh scattering is a two-vertex process given by the Feynman scheme (Fig. 1). According to first diagram 1a, the photon is absorbed first before the emitted photon while the order is reversed in the second diagram 1b. The double lines indicate that the electron in the initial, intermediate and the final states is under the influence of the central Coulomb fields of the nucleus and the other atomic electrons. Hence bound state electronic wave functions are to be used for the initial and the final states while bound and continuous state wave functions are to be used for the intermediate state. In terms of the conventional second order perturbation theory, the transition amplitu e M for Rayleigh scattering is given in the usual notation, by

$$M = \sum \frac{\langle f | H' | n \rangle \langle n | H' | i \rangle}{E_1 - E_n \pm h\nu} \tag{1}$$

the + and – sign in the denominator refer to the first and second diagrams 1a, 1b respectively. The perturbation Hamiltonian is given by

$$H' = e\underline{\alpha}\underline{A}(x), \tag{2}$$



(a) (b)

Figure 1. Feynman diagram for Rayleigh scattering.

which in the non-relativistic limit is

$$H' = \frac{ie}{mc} \underline{\nabla} \underline{A} . \tag{3}$$

Franz [1] and later Bethe [2] using Feynman method have shown that in the nonrelativistic limit and in cases where the binding in the intermediate states can be neglected, the differential cross section for the Rayleigh scattering is given by the form factor approximation

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left(\frac{e^2}{mc^2}\right)^2 (1+\cos^2\theta) \left|F(q, Z)\right|^2 , \tag{4}$$

where the form factor F is defined as

$$F(q, z) = <0 \left| \sum_{j=1}^{Z} \exp \frac{i}{\hbar} \underline{q}\underline{x}_j \right| 0> , \tag{5}$$

where $|0>$ is the ground state ket of the atom and $\underline{x}_j$ is the position vector of the j th electron in the atom relative to the nucleus. If $\rho(\underline{x})$ is the total electron density at $\underline{x}$, $F(\underline{q}, Z)$ becomes

$$F(q, Z) = \int \rho(\underline{x}) \, \exp \frac{i}{\hbar} \underline{q}.\underline{x} \, d^3x . \tag{6}$$

For a spherically symmetric charge distribution

$$F(q, Z) = 4\pi \int_0^\infty \rho(\underline{r}) \, \frac{\sin kr}{kr} \, dr , \tag{7}$$

where

$$k = \frac{q}{\hbar} . \tag{8}$$

For an element other than hydrogen, the above equation cannot be exactly solved and it is then necessary to invoke the aid of various atomic models *e.g.* Thomas-Fermi model, Hartree and Hartree-Fock self-consistent models, Dirac-Slater model *etc*. It is to be noted that the form factor eq. (4) can also be derived classically in terms of Thomson scattering, which assumes a point charge distribution while in the Rayleigh scattering calculations, finite extension of the charge in three dimensions in taken into account.

It is to be noted that in every type of form factor calculation, eq. (4) remains valid. If we define reduced differential Rayleigh scattering as

$$\frac{d\sigma'}{d\Omega} = \frac{\frac{d\sigma}{d\Omega}}{(1+\cos^2\theta)}$$

$$\overline{mc^{2}} \quad F(q, Z)|^2 , \tag{9}$$

so that the reduced cross section has no explicit dependence on E (there is implicit dependence through q, however) *i.e.* if we take q and E_r as independent variables, $\frac{d\sigma'}{d\Omega}$ should be independent of E_r. Nath and Ghose [3] using the data available at that time showed that $\frac{d\sigma'}{d\Omega}$, in fact, depends on E_r as shown in Figure 2, where lines belonging to lower energies lie below those belonging to higher energies. It is quite clear, therefore, that the form factor approximation is not adequate to describe the phenomenon of coherent scattering, a result which will continue to be valid even with the improved accuracy of experimental data. This result can further be utilised as an accurate (within experimental limits, of course) semi-empirical formulation of differential coherent scattering cross-sections [3, 4]. The formula can further serve to develop

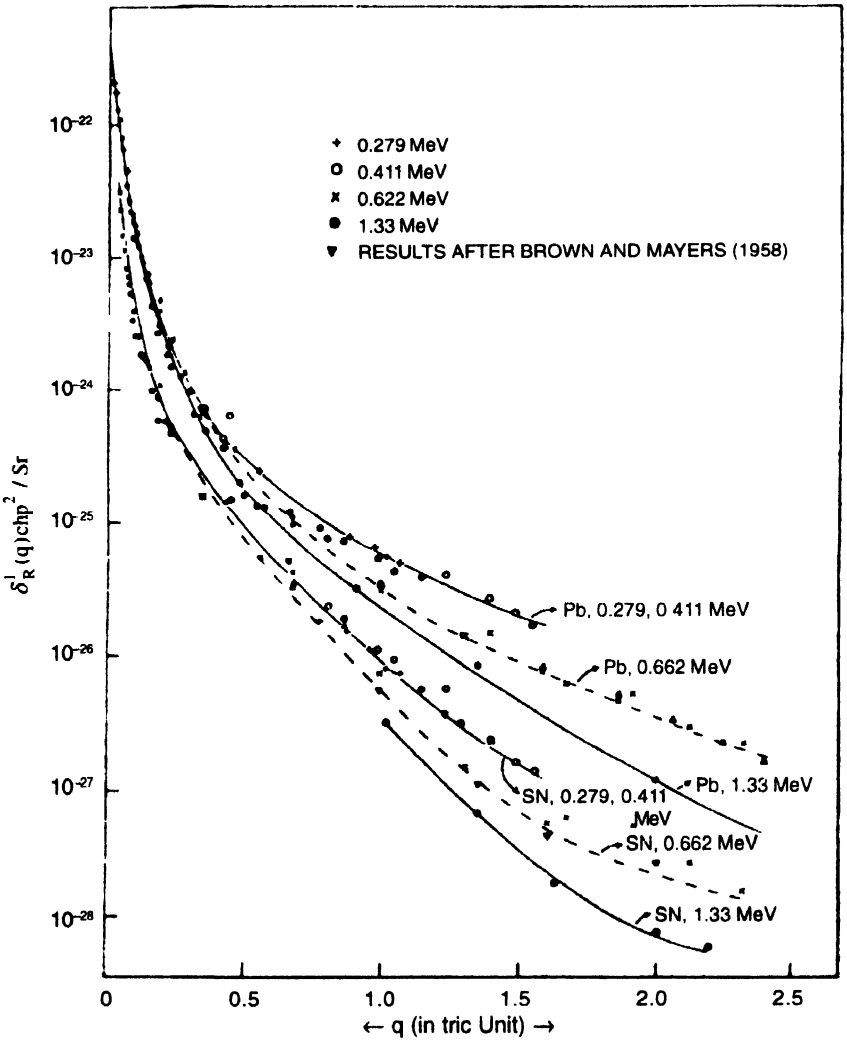


Figure 2. Experimental $\sigma' = \frac{d\sigma'}{d\Omega}$ data of Pb and Sn for different γ-ray energies plotted as a function of q

a method for semi-empirical measurement of inner shell electron distribution in high Z atoms [4]. Whereas derivation of the differential scattering cross section from the more accurate second order perturbation theory is only approximate, the reduced cross sections using Fig. 2 are more accurate. It is suggested, therefore, that the theoretical cross sections, be analysed in terms of reduced cross sections to yield a semi-empirical formula for accurate values of Rayleigh cross sections. It would also be interesting to theoretically compute cross section values for close values of E_r and examine if the energy-wise separation of reduced cross sections is really accurate or not. If they turn out to be accurate, it would be necessary to examine the theoretical basis of such separation. Again, it might be useful to change the polarisation factor $= \frac{1}{2}(1+\cos^2\theta)$ to more accurate values derived from the more accurate calculations. Obviously many more questions will occur to the reader regarding this strange behaviour of reduced cross section σ'.

3. Measurement of total cross section of gaseous samples for low energy photons

A major problem in the measurement of total cross section of gaseous samples is to provide sufficient material between the source and the detector to ensure adequate statistical accuracy of the transmission measurements. The usual method for achieving this is to use as high a pressure of the sample as possible. One has to take into account the effect of the high pressure container vessel on the background *etc*. Further, it would of advantage to reduce "dead" space which surrounds the direct beam. It would be interesting in this connection to examine the feasibility of using light rigid materials (compressed in stages if necessary) like foam plastic to pack into the dead space. For specially pure rare gases, the use of such packing materials would be economic too. Furthermore, it is almost inevitable that the measurements are to be carried out under "good geometry" conditions. In this connection one might consider the use of multi-section filter system which has been developed for small angle coherent scattering cross sections. Some of the many correction factors which must be throughly analysed and removed or reduced are :

- (a) Finite Geometry Corrections,
- (b) Multiple Scattering Corrections,
- (c) Room Scattering Corrections,
- (d) Correction for sample dependent background,
- (e) Correction for impurities present in the sample.

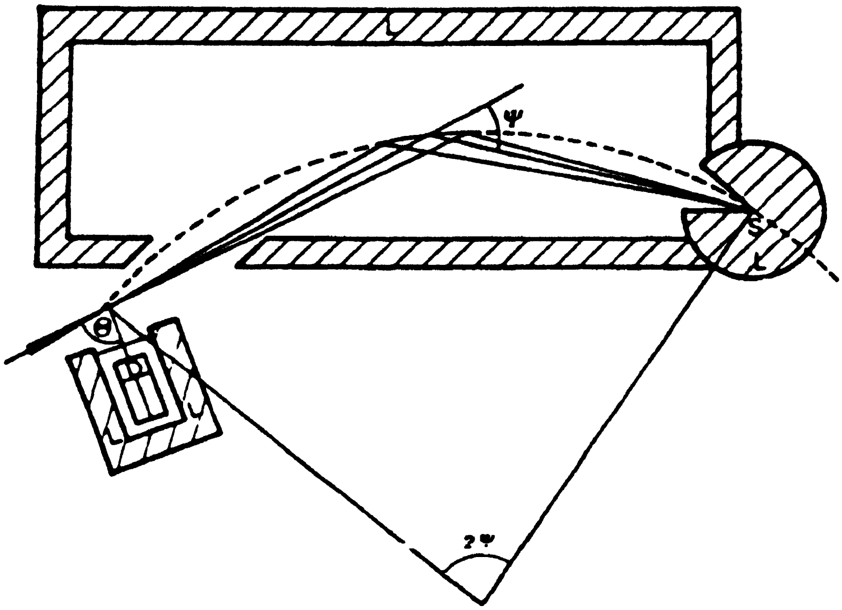
4. Cylinder transmission

Since the first application of the sphere transmission method by Collie and Griffiths [5], it has been extensively used in diverse areas in radiation physics [8-50]. However, spherical shells of uniform thickness are often difficult to cast since uniform foils can be rolled into cylindrical form rather easily and attempts were made, therefore, to explore the conditions under which cylinder transmission yielded exactly the same result as sphere transmission. It can be seen that relative to sphere transmission, cylindrical transmission emphasises the scattered radiation and hence the two transmissions can be made identical especially in the limit if the effect of scattered radiations could be compensated. We have developed several methods based on this compensation and shall be happy to discuss them with the other gleaners in the field. It must be stressed that strict cylinder transmission would require a line source of infinite extension.

We have, instead, taken a point source of radiation with finite dimension. Design of experimental set up to carry out modified cylinder transmission experiments has already been completed and hopefully measurements will be carried out soon.

5. A strong source for nuclear resonance fluorescence studies

Many authors have investigated the possibility of using Compton scattering for developing a gamma ray source of continuously variable energy over a wide energy range. Mouton [6] actually developed such a source and noted that the need for separate surface for each angle of scattering. A very elegant source based on arc geometry was developed by Tandon and McIntyre [7] (Figure 3).



S = kilocurie ^{60}Co source, C = aluminium converter
T = target whose nuclear resonance fluorescence is under study
D = detector for the measurement of radiation scattered by T
L = lead shields, Ψ = compton angle of scattering, Θ = resonance scattering angle

Figure 3. Schematic representation of the arc geometry source of continuously variable energy gamma ray photons based on Compton scattering.

It was suggested that by using a modified surface of revolution method, intensity of the beam can be considerably increased without substantially altering the energy spread of the beam. Such a method was actually tried for fast neutrons with considerable success. In order to alter the angle of scattering smoothly and continuously, it is suggested that the motion of the arcs and detector be microprocessor controlled. Some of the details have been discussed by Ghose [51].

6. Concluding remarks

We have discussed only a few of the many unsolved problems in radiation physics. A substantial number of these can be solved by simple experimental set up. Some of the unsolved theoretical problems do not require advanced computing facilities; some of them are even amenable to the use of personal calculators.

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References

[1] W Franz *Z Phys* **95** 652 (1935) ; **98** 314 (1936)

[2] H Bethe Private communication quoted by A Storruste *Proc Phys Soc* **A63** 1157 (1950)

[3] A Nath and A M Ghose *Nat. Bur Std Tech* notes No. 442 (U S , G.P O Washington) (1968)

[4] S C Roy and A M Ghose *Phys Rev* **A8** 2296 (1973)

[5] C H Collie and J H E Griffiths *Proc Roy Soc (London)* **155A**, 434 (1936)

[6] W L Mouton *et al Phys. Rev.* **129** 361 (1963)

[7] G A Tandon & J A McIntyre *Nucl Instrum Meth* **59** 181 (1968)

[8] L Szilard, S Bernstein, B Feld and J Ashkin *Phys Rev* **73** 1307 (1949)

[9] H T Gittings, H H Barschall and G G Everhart *Phys Rev* **75** 1610 (1949)

[10] H H Barschall *Rev Mod Phys* **24** 120 (1952)

[11] D D Philips, R W Davis and R A Nobles *Phys Rev* **88** 600 (1952)

[12] E Amaldi, D Bocciarelli, B N Cacceiapuotti and G C Trabacchi *Rep Intl Conf Phys Soc (London)* **1** 97 (1947) ; *Nuovo. Cim* **3** 203 (1946)

[13] J R Beyster, R L Henkel and R A Nobles *Phys Rev* **97** 563 (1955)

[14] E R Graves and R W Davis *Phys Rev* **97** 1205 (1955)

[15] J R Beyster, R L Henkel and R A Nobles and J M Kister *Phys Rev* **98** 1216 (1955)

[16] H L Taylor, O Lonsjo and T W Bonner *Phys Rev* **100** 174 (1955)

[17] R Batchleor *Proc Phys Soc (London)* **69A** 214 (1956)

[18] J M Freeman *Prog Nucl Phys* **5** 38 (1956)

[19] L Cranberg, R B Day, L Rosen, R F Taschek and M Watt *Prog Nucl Energy* **I**, Ser 1, p. 107 (1956)

[20] M B Pasechnik *Proc Intl Conf Peaceful Uses of Atomic Energy* (Geneva) **2** 3 (1956)

[21] J R Beyster, M Walt and E W Salmi *Phys Rev* **104** 1319 (1957)

[22] N M Flerov and V M Talyzin *J Nucl Energy* **4** 529 (1957)

[23] V I Strizak *J Nucl Energy* **5** 253 (1957)

[24] R C Allen *Phys Rev* **105** 1796 (1957)

[25] M H MacGregor, W P Ball and R Booth *Phys Rev* **108** 726 (1957)

[26] R C Allen- *Nucl Sci Engg* **2** 787 (1957)

[27] W P Ball, M H MacGregor and R Booth *Phys Rev* **110** 1392 (1958)

[28] M H MacGregor, W P Ball and R Booth *Phys Rev* **111** 1155 (1958)

[29] M H MacGregor *Proc Intl Conf Peaceful Uses of Atomic Energy* (Geneva) **14** 109 (1958)

[30] V N Andreev *J Nucl Energy* **9** 151 (1959)

[31] R C Allen, R E Carter and H L Taylor in *Fast Neutron Physics*, eds J B Marion and J L Fowler (London : Interscience) **II**, p 1429 (1963)

[32] K W Allen, P Bomyer and J L Perkin *J Nucl Energy* **A/B 14**, 100 (1961)

[33] A V Cohen *J. Nucl. Energy* **A/B 14** 180 (1961)

[34] D Didier and H Dilleman *J. de Phys* **24** 805 (1963)

[35] M H Mac Taggart and H Goodfellow *J Nucl Energy* **A/B 17**, 437 (1963)

[36] M H MacGregor, W P Ball and R Booth *Phys Rev* **130** 1471 (1963)

[37] G M Hass and P L Okhuysen *Phys Rev.* **132** 1211 (1963)

[38] Yu G. Degtyarev *J Nucl. Energy* **19** 1426 (1965)

[39] I A Korzh, M V Pasechnik and I A Totskii *J Nucl. Energy* **20** 8 (1966)

[40] Yu G Degtyarev *J. Nucl. Energy* **20** 818 (1966)

[41] A Chatterji and A M Ghose *Phys. Rev.* **161** 1181 (1967)

[42] F Boreli, B B Kinsey and P N Srivastava *Phys Rev* **174** 1147 (1968)

[43] J Csikai *At Energy Rev.* **11** 415 (1973)

[44] B Pal, A Chatterjee and A M Ghose *Nucl Instrum Meth.* **171** 347 (1980)

[45] B Shanglian, Z Wenguang, S Zhaomin, T Guaoyou, C. Jinxiang and Z Chonghou IAEA Report No INDC (CPR)-003/L International Atomic Energy Agency (Vienna), (1985)

[46] N K Ganguly and A M Ghose *Indian J. Phys* **30** 500 (1956)

[47] A M Ghose and N K Ganguly *Indian J Phys* **31** 285 (1956)

[48] A M Ghose *Trans Bose Res Inst* **24** 7 (1961)

[49] *For Reciprocal Sphere Transmission,* D D Phillips, *Los Al Lab. Rep* **744** (1949) , H A Bethe *Los Al Lab. Rep.* **LA 1428** (1952)

[50] H A Bethe, J R Beyster and R A Carter *J Nucl Energy* **3** 207, 273 (1956) , **4** 3, 147 (1957)

[51] A M Ghose *Optimisation and Symmetry in Experimental Radiation Physics.* Published by the Commission of the European Countries- Luxemberg (1987)

For neutron sources see—

D Arran, S Singkriat *Nucl Instrum. Meth.* **A245** 426 (1986)

A M Ghose *Nucl. Instrum Meth.* **A280** 322 and earlier references there in (1989)